

Soil moisture dynamics and smoldering combustion limits of pocosin soils in North Carolina, USA

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Abstract. Smoldering combustion of wetland organic soils in the south-eastern USA is a serious management concern. Previous studies have reported smoldering was sensitive to a wide range of moisture contents, but studies of soil moisture dynamics and changing smoldering combustion potential in wetland communities are limited. Linking soil moisture measurements with estimates of the sustained smoldering limits of organic soils will improve our understanding of changes in ground fire potential over time. Seasonal soil moisture trends were monitored in six North Carolina coastal plain pocosin sites from January 2005 to November 2007. Measurements of the root-mat upper soil horizons were sampled at 2-week intervals while measurements of lower horizon muck (sapric) soil moisture contents and watertable depths were made with automated data logging equipment. The watertable and soil moisture responses were influenced by seasonal and yearly differences in precipitation and hydrologic factors. The maximum estimated probabilities of sustained smoldering were highest in the fall of 2007 and lowest in 2006. Watertable depth was not a consistent predictor of the smoldering combustion potential in the upper organic soil horizons. Maximum Keetch–Byram Drought Index values on all sites were between 500 and 662 during 2005 and 2007 and these values were not consistent with measured soil moistures.

Introduction

Pocosin wetlands formed along the coastal plain of the eastern US through the interaction of water, climate and topography. The accumulation of peat on the coastal plain that began after the end of the Wisconsin Glacial Age between 10 340 and 8135 years before present was the result of changing climate and a rising sea level (Daniel 1981). Peat accumulated in the depressions and basins associated with ancient rivers and sounds and eventually organic soil mantled the ancient landscape. As wetland development continued, the extent and thickness of the organic soil layer increased. The median thickness of the peat layer of the North Carolina coastal plain is 1.4 m and the maximum depth ranges from 4.6 to 6 m (Ingram 1987).

The vegetation communities present in the pocosin wetlands are dominated by evergreen sclerophyllous shrub species (Weakly and Schafale 1991). These species are tolerant of frequently saturated acidic organic or mineral soils, with low nutrient availability and thick organic horizons (Daniel 1981; Sharitz and Gibbons 1982). The pocosin plant communities are common on the south-eastern coastal plain of the United States from Virginia to northern Florida and west to Alabama (Richardson 2003). In North Carolina, several freshwater wetland types occur on the coastal plain and pocosin wetlands comprise 14.5% of the total wetland area (Sutter 1999).

Several distinct pocosin community types have been recognized in North Carolina. Their distribution occurs on landscape positions with a broad range of topographic and physiographic characteristics that reflect gradients in organic soil depth, hydrologic processes and fire frequency (Weakly and Schafale 1991).

Kologiski (1977) reported that the distribution of pocosin communities in the Green Swamp in south-eastern North Carolina was a result of the interaction of organic soil depth, hydrology and fire frequency. Frost (2000) reported that the distribution of communities in peatlands was the result of soil fertility, organic soil depth and fire frequency. If undisturbed by fire, peat accumulates above the watertable and the amount and ratio of live to dead surface fuel increases. These changes contribute to an increase in the likelihood of fire (Christensen *et al.* 1981).

The development and depth of most histosols in North Carolina have been affected by smoldering combustion (Lilly 1981) and a range of fire return intervals was reported for wetland community types associated with these organic soils (Wells 1942; Ash *et al.* 1983; Sharitz and Gresham 1998; Frost 2000). The reported return intervals in Low Pocosin community types, characterized by long hydroperiods and nutrient limited deep organic soils, ranged from 13 to 50 years (Sharitz and Gresham 1998). Whereas the reported return intervals in High Pocosin community types, characterized by shorter hydroperiods and less nutrient limited thinner organic soils, ranged from as low as 5 to 8 years or as long as 10 to 50 years (Ash *et al.* 1983). Pond Pine Woodland community types were found on similar soils but were present on more productive sites resulting from a shorter hydroperiod and thinner organic soil horizons. Return intervals in that community type were reported from 10 to 30 years (Wells 1942), whereas return intervals as low as 3 to 5 years were reported in Pond Pine communities with a switch cane (*Arundinaria gigantea*) understorey (Frost 2000).

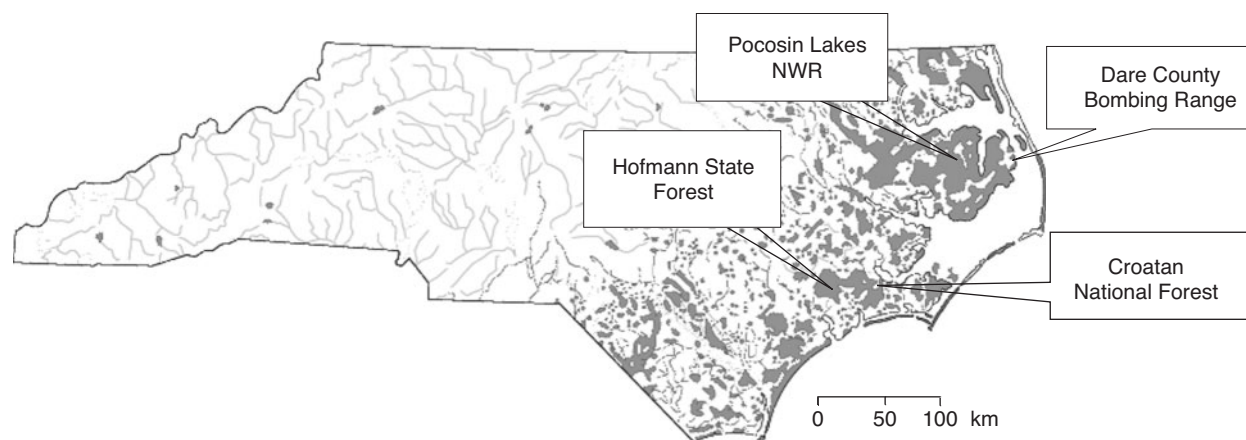


Fig. 1. Widespread distribution of wetlands and the location of sample sites on the coastal plain of North Carolina (adapted from Dahl 1991).

Although fire return interval and fire frequency are common measures reported for surface fires in vegetation communities, there is no equivalent measure that characterizes the frequency of ground fires. Control of fire severity and organic soil consumption in pocosin and associated community types has been partially attributed to hydroperiod (Kologiski 1977). Surface fires that occur when the soil is saturated can consume significant amounts of surface fuel with limited organic soil consumption. However, fires that occur when soils have low moisture contents can result in substantial consumption of surface and organic soil.

A range of duff and organic soil moisture limits to smoldering combustion are reported in the literature. A limit of 40% moisture content on a dry weight basis has been reported for organic soils from Florida (Bancroft 1976), whereas McMahon *et al.* (1980) reported smoldering at moisture contents as high as 135% in organic soils from south central Florida. Frandsen (1997) reported that pocosin muck soils with a moisture content of 145% would sustain smoldering 50% of the time. Recent work by Reardon *et al.* (2007) reported that root-mat soils from pocosin sites on the North Carolina plain with moisture contents greater than 145% and a mean mineral content of 4.5% had an estimated probability of sustained smoldering of less than 10% whereas highly decomposed muck soils with moisture contents greater than 260% would have less than a 10% estimated probability of sustained smoldering.

At present, tools for predicting the potential of wetland ground fire are limited. Shallow watertable wells and the water levels in drainage ditches are commonly used by land managers as an informal indicator of localized ground fire potential in pocosins. Regional estimates of ground fire potential are commonly evaluated using the Keetch–Byram Drought Index (Keetch and Byram 1968).

The Keetch–Byram Drought Index (KBDI) is calculated from weather data at specific locations and is commonly used to describe moisture conditions over broad areas while ignoring finer-scale differences. The index is often used to estimate the seasonal cumulative moisture deficiency of organic materials in the upper soil horizons and the deeper duff (Keetch and Byram 1968). Index values in the 200 to 400 range are representative of late spring and early summer conditions, when litter and duff

moisture contents decrease and these fuels begin to contribute to fire intensity. Increased values in the 400 to 600 range reflect summer and early fall burning conditions. Under these conditions, the moisture contents of the duff and associated organic layers are low enough to ignite and the consumption of duff and organic soil is expected to contribute to fire intensity. Values above 600 reflect severe drought conditions and the likelihood of significant duff and organic soil material consumption (Melton 1989, 1996).

We propose that linking the sustained smoldering limits of root mat and muck soils with soil moisture measurements can increase our understanding of seasonal influences on ground fire potential and improve the effectiveness of fire danger rating in pocosin communities. The present discussion integrates soil moisture measurements made at regular intervals on North Carolina coastal plain pocosin sites from 2005 to 2007 (Bartlette *et al.* 2005) with the moisture limits of sustained smoldering of organic soils from the similar coastal plain pocosin sites (Reardon *et al.* 2007).

Methods

Sample sites

Representative sample sites were selected from large contiguous areas of pocosin wetlands on the North Carolina coastal plain. Sample sites were selected on the Hofmann State Forest, Pocosin Lakes National Wildlife Refuge (NWR), the US Air Force Dare County Bombing Range (DCBR), and the Croatan National Forest (NF) (Fig. 1). Watertable depth and soil moisture measurements were made at regular intervals from 2005 to 2007. A total of six study sites were monitored.

Two study sites were monitored at Hofmann State Forest. The Wide Open Road site is a High Pocosin community type dominated by a dense fetterbush (*Lyonia lucida*) shrub layer with scattered and stunted pond pine (*Pinus serotina*), red bay (*Persia borbonica*) and loblolly bay (*Gordonia lasianthus*). The Pocosin Road site is located within 8 km of the Wide Open Road site. It is a Pond Pine Woodland community type that is dominated by a nearly closed pond pine overstorey with a red and loblolly bay midstory and a cyrilla (*Cyrilla racemiflora*) shrub understorey.

Watertable depth, root-mat soil moisture and muck soil moisture data for this site were collected from 2005 to 2007.

One sample site was monitored on the Pocosin Lakes NWR. The Allen Road site burned in the 1985 Allen Road fire. This site is a High Pocosin community dominated by a fetterbush shrub layer with scattered pond pine, loblolly bay and red bay. Watertable depth, root-mat soil moisture and muck soil moisture data for this site were collected from 2005 to 2007.

Two study sites were monitored on the DCBR. The Lake Worth Road was a High Pocosin community type dominated by a dense gallberry (*Ilex glabra*) shrub layer with a scattered pond pine overstorey. The Long Curve Road site was a Pond Pine Woodland community type dominated by a nearly closed pond pine overstorey with loblolly bay, red bay and a red maple (*Acer rubrum*) midstory with a scattered shrub understorey of gallberry and fetterbush. This site is located within 8 km of the Lake Worth Road site. Watertable depth and muck soil moisture data for this site were collected from 2005 to 2007. Root-mat soil moisture data on these sites were collected from January to late July 2007.

One sample site was monitored on the Croatan NF. This site was a High Pocosin community with scattered pond pine, red bay and loblolly bay and dominated by a fetterbush and cyrilla shrub layer. Watertable depth and muck soil moisture data for this site are available from 2005 to 2007. Root-mat soil moisture data were collected from January to late July 2007.

Precipitation data

Precipitation data were obtained from the Remote Automated Weather Station (RAWS) network maintained by the North Carolina Department of Forest Resources (NCDNR). Local weather data were obtained from the Hofman Forest, Pocosin Lakes NWR and Croatan NF, and data for the DCBR sites were obtained from Alligator River NWR.

Precipitation data were summarized in annual totals and graphically as double mass plots.

Double mass plots are a method of examining the consistency or homogeneity of rainfall data with data from surrounding weather stations (Searcy and Hardison 1960). Double mass plots were constructed to compare the cumulative monthly rainfall of each RAWS station with the 20-year-mean cumulative monthly rainfall from five additional weather stations within the study area.

Watertable depth and soil moisture

Watertable depth measurements were collected with automated monitoring wells (Remote Data Systems, Whiteville, NC). Each site was instrumented with one well, and watertable depths relative to the soil surface were recorded four times daily at depths of up to 110 cm below the ground surface.

The soils at all study sites are characterized by three major organic horizons that are of concern in fire management. The typical surface organic horizon (Oe) is composed of needle, leaf and twig litter of intermediate (hemic) decomposition. This horizon is typically 0 to 10 cm thick. The root-mat soil horizon (Oa1) is an intermediate horizon consisting of highly decomposed organic material of granular structure. The thickness of this horizon is typically 0 to 30 cm. The muck or sapric soil

horizon (Oa2) consists of highly decomposed organic material of massive structure. The thickness of this horizon is typically 25 to 127 cm (Tant 1992). The present study focuses on the soil moisture dynamics of the root-mat and muck soil horizons.

Because there are no automated methods for the measurement of root-mat soil moisture, this was measured by destructive sampling. The surface topography of the pocosin vegetation types is highly variable and is often described as hummock and depression or hummock and hollow microtopography. Small elevation changes of 0.5 to 0.9 m are common over distances of 1.0 to 3.0 m in pocosin vegetation types. Root-mat samples were collected from mid hummock elevations at 2-week intervals. Gravimetric moisture content of the root-mat samples was determined after the samples were oven-dried at 90°C for a minimum of 48 h. Three samples were collected at each site at the 2-week intervals unless there was precipitation on the scheduled collection day. A total of 537 root-mat samples were collected during the current study.

Muck soil moisture measurements were conducted with soil moisture probes (CS 615 Campbell Scientific, Logan, UT) and measurements were recorded at hourly intervals on a data logger (SGT Engineering, Champaign, IL). The moisture probes were placed at the root mat–muck soil interface. One probe inserted vertically measured average moisture content along its 30-cm length, while the second probe, which was inserted at a 45° angle, measured the average moisture at 15-cm depths. The soil moisture probes were calibrated to muck soil gravimetric moisture content using a four-point calibration curve. A single curve was applied to the muck (sapric) soils on all sites. The data were summarized by weekly means from January to November of each year.

Sustained smoldering probabilities

The moisture limits of smoldering combustion in root mat and muck soils from North Carolina coastal plain wetlands were determined in a previous study and predictive relationships between moisture content and the probability of sustained smoldering were developed for root mat and muck soils (Reardon *et al.* 2007). The 2007 study contains a detailed description of the laboratory and analysis methods.

Soil moisture measurements were used to calculate estimated probabilities of sustained smoldering in root mat (Eqn 1) and muck soils (Eqn 2). The mean root-mat mineral content of each site was determined. The mineral content of five samples from each site was determined by ashing the samples in a muffle furnace at 450°C for 24 h.

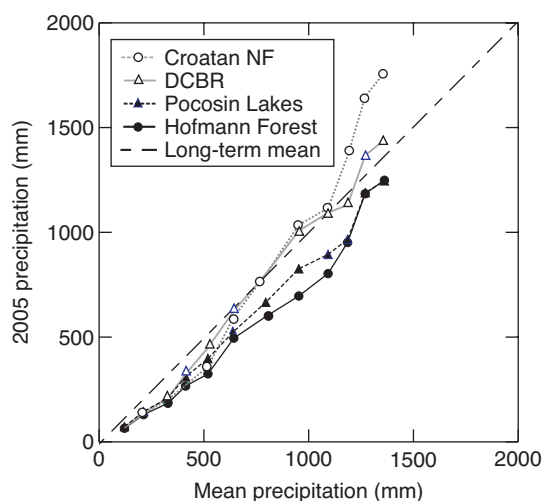
The estimates from Eqns 1 and 2 are the probability that the root mat and muck soil will sustain smoldering combustion after ignition. The estimated probabilities were summarized as weekly mean estimated smoldering potential from January through November.

$$\begin{aligned} \text{Probability of sustained smoldering in root-mat soils} \\ = 1 / (1 + e^{-(2.033 - 0.43 \times \text{moisture content} + 0.44 \times \text{mineral content})}) \end{aligned} \quad (1)$$

$$\begin{aligned} \text{Probability of sustained smoldering in muck soils} \\ = 1 / (1 + e^{-(7.653 - 0.038 \times \text{moisture content})}) \end{aligned} \quad (2)$$

Table 1. Study site precipitation (mm) 2005–07

Location	2005	2006	2007
Hofmann State Forest	1253	1476	936
Dare County Bomb Range	1428	1569	1143
Pocosin Lakes National Wildlife Refuge	1268	1433	917
Croatan National Forest	1803	1639	1244

**Fig. 2.** Double-mass plot of 2005 cumulative monthly precipitation and 20-year mean cumulative monthly precipitation.

KBDI and fire occurrence data

Daily KBDI values were calculated with RAWs data from Hofmann State Forest, Pocosin Lakes NWR, Alligator River NWR and Croatan NF weather stations.

The number of fires and hectares burned in 2005 and 2006 was compiled from the NCDNR occurrence database. The data were summarized for 20 counties on the North Carolina coastal plain with organic soils.

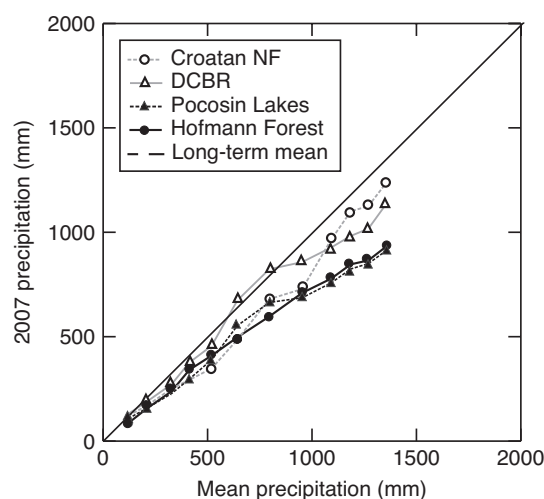
Results

Precipitation

Annual total precipitation on the study sites ranged from 917 to 1803 mm (Table 1). The lowest total precipitation during this period was recorded at the Hofmann Forest and Pocosin Lake NWR site in 2007 whereas the highest annual precipitation was on the Croatan NF site in 2005.

In 2005, precipitation was below the long-term cumulative monthly average throughout the year on the Hofmann Forest and Pocosin Lake sites. Precipitation on the Croatan NF and DCBR sites increased in late spring and was above the long-term average on those sites during the remainder of the year (Fig. 2).

In 2006, rainfall fell below the long-term cumulative monthly average from January through July on all sites. Precipitation during the remainder of the year was average to above average

**Fig. 3.** Double-mass plot of 2007 cumulative monthly precipitation and 20-year mean cumulative monthly precipitation.

on the Pocosin Lakes, Croatan and DCBR sites but remained below average on the Hofmann Forest site until December.

In 2007, precipitation fell increasingly below the long-term averages on the Pocosin Lakes, Hofmann Forest and Croatan NF sites. Rainfall on the Croatan NF site was greater than the other sites during the late summer and fall but remained below the long-term average. In comparison with the other sample sites, the rainfall on the DCBR was more variable. It was below average during the winter and early spring and again in the late fall and it was average during the summer months (Fig. 3).

Watertable

Between 2005 and 2007, the range of maximum watertable depths across the study sites varied from 34.0 cm to lower than 110.0 cm. The maximum depth was lower than 110 cm on the Hofmann Forest Wide Open Road site in 2005 and in 2007. In contrast, maximum watertable depths were consistently closer to the soil surface on the DCBR Lake Worth Road and Long Curve Road sites. In 2007, the maximum depths were 29.0 and 38.0 cm, respectively.

In 2005, the watertable depths fluctuated from 0 cm to lower than 110.0 cm below the soil surface. Watertable levels reached their deepest levels in early September. At that time, depths on the Wide Open Road and Pocosin Road sites on the Hofmann Forest were greater than 100 cm. In comparison, the maximum watertable depths on the Lake Worth Road and Long Curve Road DCBR sites were 34.0 and 37.0 cm, respectively (Fig. 4).

During 2006, watertable depths fluctuated from 0 to 112.8 cm below the soil surface. The results show no seasonal decline in water-level depth measurements. The lowest watertable depths were measured on the Wide Open Road site in October. Watertable depths remained above 40.0 cm on the Long Curve Road, Lake Worth Road and Pocosin Lakes sites in 2006 (Fig. 5).

In 2007, watertables fluctuated from near the soil surface to 110 cm. Watertable measurements showed a sharp decline from August through November. During the fall, watertable levels were below 100.0 cm on the Hofmann Forest and Pocosin

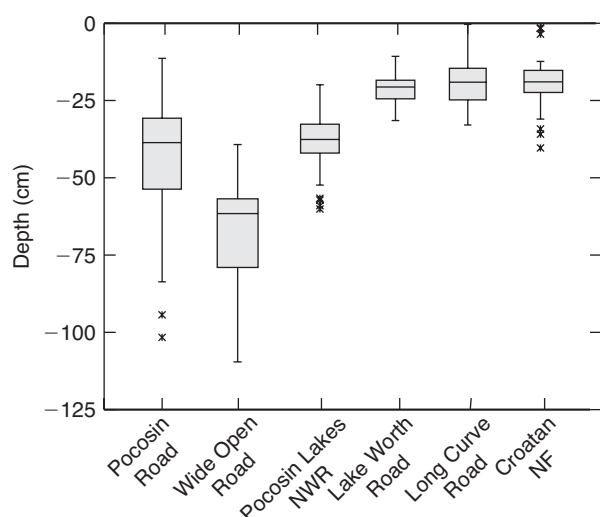


Fig. 4. Box plots of mean weekly watertable depths from January to November 2005.

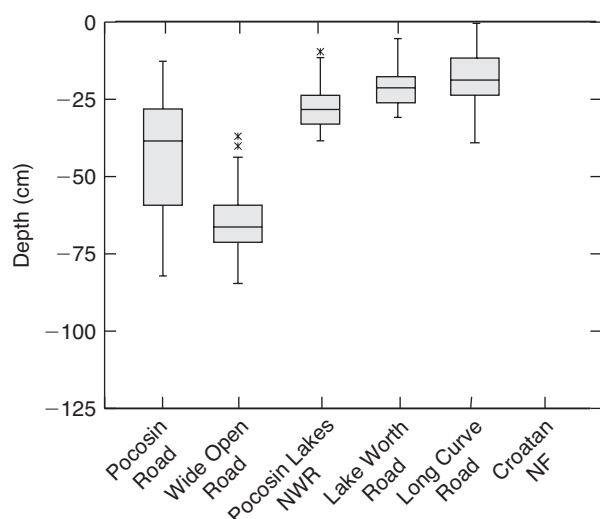


Fig. 5. Box plots of mean weekly watertable depths from January to November 2006. Data from the Croatan National Forest site was not available owing to equipment malfunction.

Lakes sites. In comparison, the lowest watertable depths on the Lake Worth and Long Curve Road sites were 59.5 and 74.2 cm, respectively, and the maximum watertable level on the Croatan NF site was 70.1 cm (Fig. 6).

Root-mat moisture

During the present study, the range of minimum root-mat soil moisture on the Pocosin Lakes and Hofmann Forest sites was 64 to 167%. The 2005 minimum root-mat moistures were 64% on the Pocosin Lakes site and 83 and 171% on the Hofmann Forest Wide Open Road and Pocosin Road sites. In 2006, minimum moistures ranged from 64% on the Pocosin Lakes site to 124 and

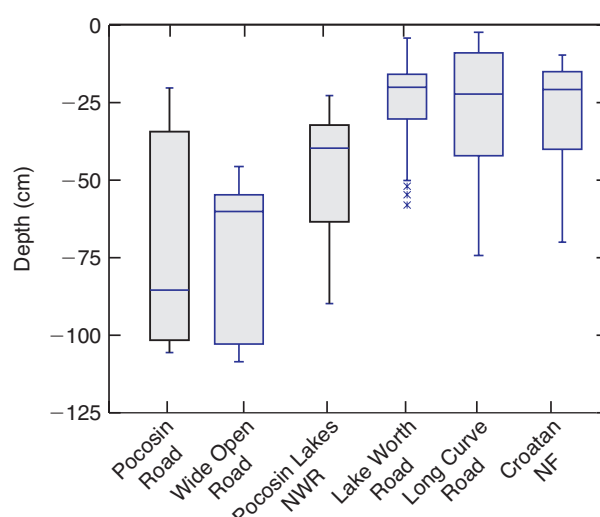


Fig. 6. Box plots of mean weekly watertable depths from January to November 2007.

146% on the Wide Open Road and Pocosin Road sites, respectively. The minimum moisture content range on these sites from January to August was 94% on the Wide Open Road, 112% on the Pocosin Lakes NWR, and 161% on the Pocosin Road sites.

The DCBR and Croatan NF sites were sampled from January through August in 2007. Minimum moisture contents below 166% were measured on the Croatan and Lake Worth Road sites in late June and early July while root-mat moisture content of the Long Curve Road site was above 225% that time. Root-mat moistures increased in late July and moisture contents on all sites were above 220% at that time.

Muck soil moisture

During the present study, the minimum moisture content ranges for the 15-cm and 30-cm soil depths were 171.8 to 454.5% and 161.8 to 446.8%, respectively. The lowest minimum moisture contents of the 15-cm and 30-cm depths were at the Wide Open Road site in 2005 and 2007. In contrast to the low minimum soil moisture of the Wide Open Road site, the minimum soil moistures were consistently higher on the Croatan NF site.

In September and October 2005, the 15-cm muck soil moisture was lowest on the Wide Open and Lake Worth Road sites. Minimum 30-cm soil depth moisture contents of 118 and 241% were present on the Wide Open and Lake Worth Site Road sites in late August to early September while the moisture contents on the other study sites were greater than 275% throughout the year (Fig. 7).

In 2006, the minimum muck soil moisture content range for the 15-cm soil depths was 224.4 to 446.8% while the minimum moisture content range for the 30-cm depth was 266.6 to 454.5%. The lowest 15-cm moisture content was on the Lake Worth Road site in July and the soil moisture at the other sites remained above 250% throughout the year. A minimum 30-cm-depth moisture content of 266.6% was present on the Wide Open Road site in July and at all other sites, the minimum 30-cm-depth soil moisture was above 300% throughout the year (Fig. 8).

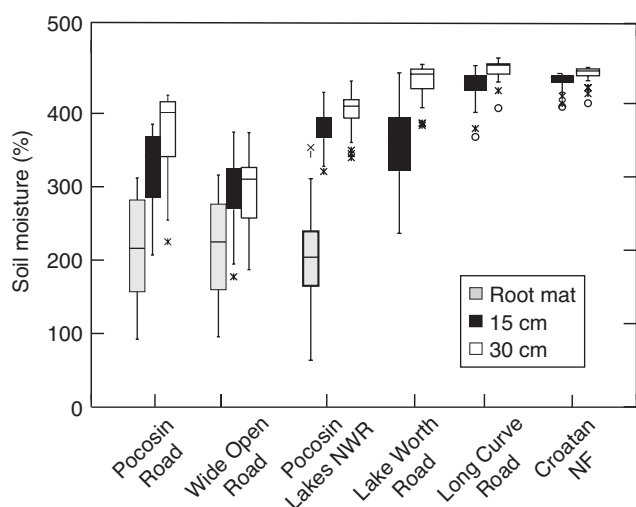


Fig. 7. Box plots of mean weekly root-mat, 15-cm depth soil and 30-cm depth soil moisture contents from January to November 2005. Data from the Long Curve Road site was collected from April to November owing to equipment malfunction.

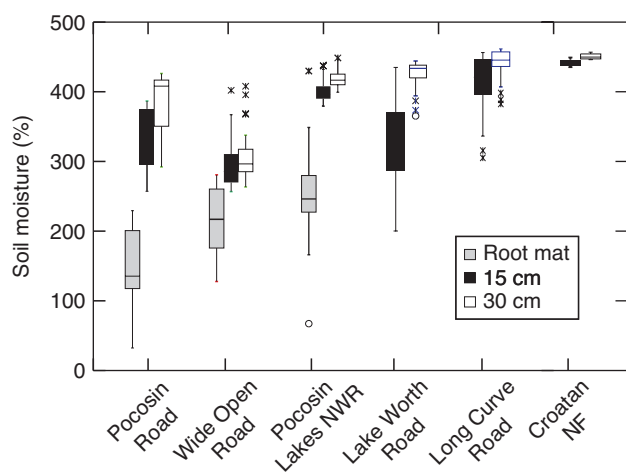


Fig. 8. Box plots of mean weekly root-mat, 15-cm depth soil and 30-cm depth soil moisture contents from January to November 2006 on all sites.

The 2007 minimum soil moisture content range of the 15-cm soil depth was 177.6 to 330.7%. The minimum soil moisture content range of the 30-cm soil depth was 161.8 to 341%. The lowest 15-cm depth minimum moisture content was found on the Wide Open Road site in October (Fig. 9).

Estimated smoldering potential – root-mat soil

The range of maximum estimated smoldering potentials of the root-mat soils on the Hofmann Forest and Pocosis Lakes sites was 69% to less than 5%. Smoldering potentials were greater than 60% on the Pocosis Lakes and Wide Open Road site in August and early September 2005. At that time, root-mat smoldering potential on the Pocosis Road site was less than 20%.

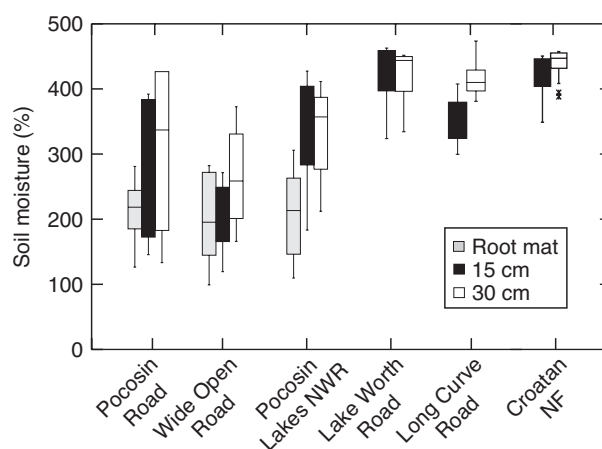


Fig. 9. Box plots of mean weekly root-mat, 15-cm depth soil and 30-cm depth soil moisture contents from January to November 2007 on all sites.

Smoldering potential was lower in 2006 on all sites except the Pocosis Lakes site, where it was 60% for a single sampling period in June. Root-mat moisture on that site increased in July and the smoldering potential remained low throughout the summer and fall.

In 2007, root-mat smoldering potentials on the Wide Open Road and Pocosis Lakes sites were greater than 50% in June and early July. Smoldering potential on both sites declined to less than 20% by early August when sampling ended. Root-mat smoldering potential on the remaining sites was below 15% throughout July and early August.

Estimated smoldering potential – muck soil

During the study period, the maximum estimated smoldering potentials of the 15-cm and 30-cm muck depths ranged from less than 1 to 59.7% and less than 1 to 61.2%, respectively. The maximum estimated smoldering potentials were highest in 2007 and lowest in 2006.

In 2005, the maximum estimated smoldering potentials of 15-cm and 30-cm muck soil depths were greater than 50% on the Wide Open Road site in August through early September, whereas the estimated potential of the 15-cm depth Lake Worth Road site exceeded 30% in October. The maximum estimated potentials of both soil depths at the other sites were less than 10% throughout the year.

The maximum estimated smoldering potentials in 2006 ranged from 31% for the 15-cm depths at the Lake Worth Road site to 21 and 19% for the 15-cm and 30-cm depths at the Wide Open Road sites, respectively. The estimated smoldering potential was less than 11% for both soil depths on the remaining study sites.

Estimated smoldering potentials in 2007 ranged from 7.0 to 59.7% in the 15-cm soil depth and 6.0 to 61.2% in the 30-cm soil depth. The highest estimated potentials were on the Wide Open and Long Curve Road sites in October while estimates for the Pocosis Road and the Pocosis Lakes sites at that time

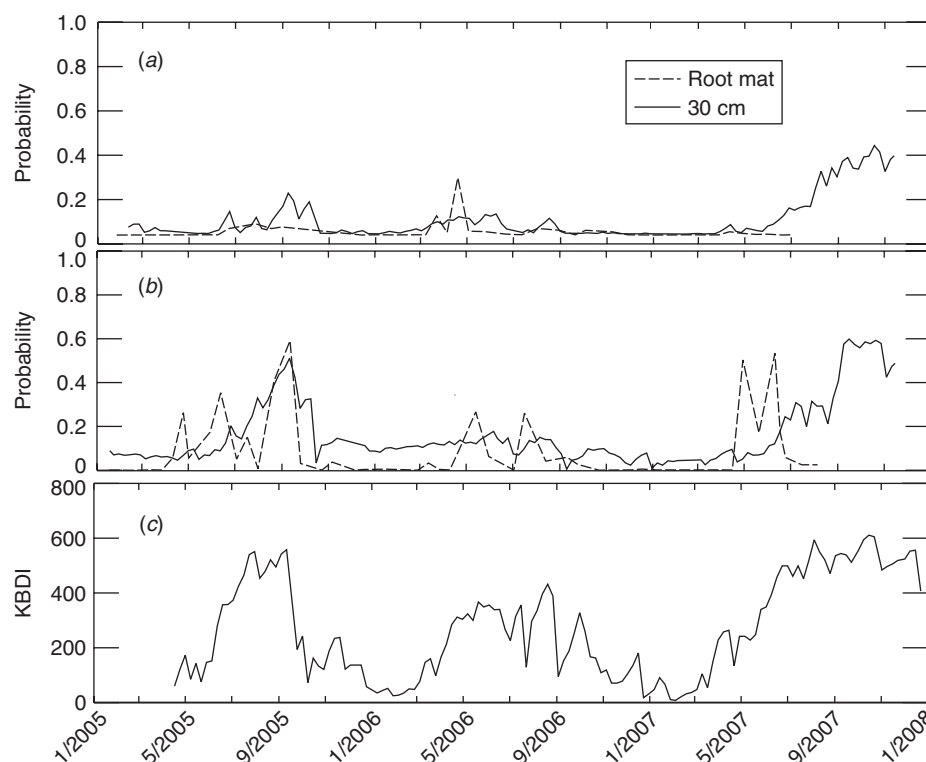


Fig. 10. Hofmann Forest 2005 to 2007, Keetch–Byram Drought Index (KBDI) values (a) and root-mat and 30-cm soil depth estimated smoldering probabilities from Wide Open Road (b); Pocosin Road (c).

were greater than 40%. The maximum estimated smoldering potentials at the Croatan site were less than 7% at that time.

Keetch–Byram Drought Index

During the present study, maximum KBDI values ranged from 379 to 662. Weekly maximum KBDI values on all sites were between 500 and 600 during the summer months in 2005 and 2007.

The 2005 maximum values ranged from 512 to 600 and the highest values were present on the Pocosin Lakes site, while the lowest values were present on the Croatan NF site. The Pocosin Lakes maximum weekly KBDI values reached 600 in early September and remained above 550 during the remainder of September 2005.

The maximum 2006 values were lower than the 2005 and 2007 values. The maximum KBDI values on the DCBR sites were above 500 and maximum values were below 500 on the Hofmann Forest and Croatan NF sites. The maximum value on the Pocosin Lakes NWR site was below 400 during the summer months.

In the late summer and fall of 2007, KBDI values exceeded 600 on all sites except the Croatan NF site. The maximum value on the Croatan NF site in the fall was 593.

Fire occurrence

From 1995 to 2006, fire occurrence in coastal plain counties with organic soil was lowest in 2003 and highest in 2001, and fire occurrence in 2005 and 2006 was consistent with the

longer-term averages. In 2005, 574 fires burned 1042 ha on the coastal plain, while in 2006, 562 fires burned 2054 ha. Fires during 2005 and 2006 were most frequent in March and April. In 2005, 46% of the recorded fires occurred in March and April, while in 2006, 69% of the recorded fires occurred during that time.

Comparisons of soil moisture, estimated smoldering potential and KBDI

On all study sites, the total precipitation in 2005 was below long-term cumulative monthly averages during the first half of the year. The maximum KBDI values of the study sites ranged from 513 to 600 in August to early September. These values suggested that the soils on all sites would support combustion. During that time, the estimated smoldering potential was lowest on the Croatan NF site where a maximum KBDI value of 513 was not consistent with the low smoldering potentials and high soil moisture content. Maximum KBDI values on the Hofmann Forest site did not reflect differences in the estimated smoldering potentials of the Wide Open Road and Pocosin Road sites (Fig. 10). A KBDI value of 600 at that time was consistent with root-mat and muck soil smoldering estimates for the Wide Open Road site that exceeded 60%, but estimates were not consistent with results from the Pocosin Road site, where the smoldering potential was less than 21% in the root mat and muck soils.

Comparisons of the 2005 estimated smoldering potentials with the maximum KBDI values for the other study sites show

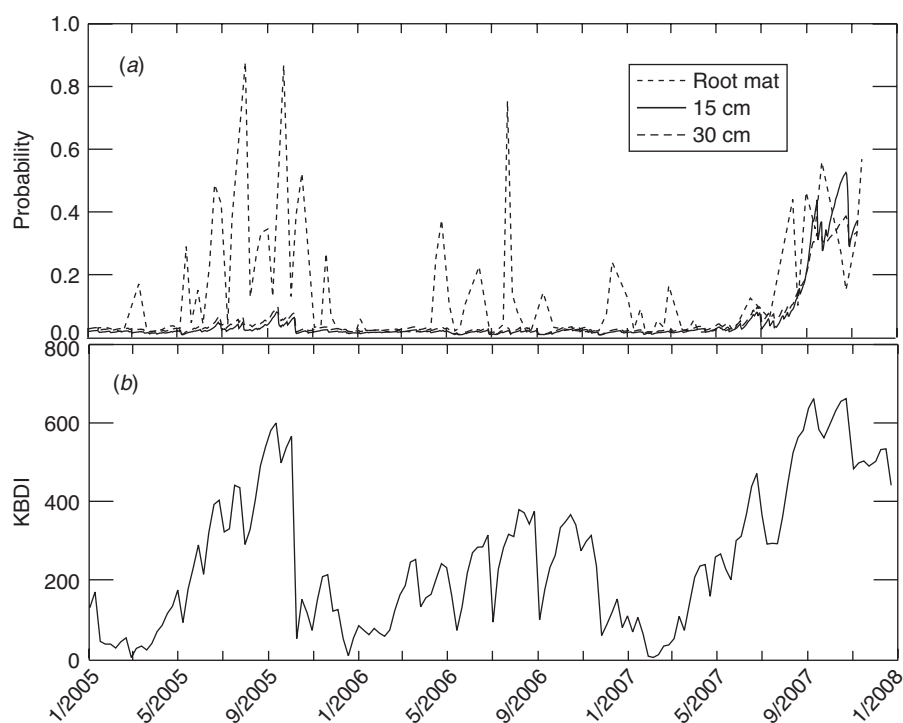


Fig. 11. Pocosin Lakes National Wildlife Refuge 2005 to 2006, Keetch–Byram Drought Index (KBDI) values (a) and root-mat, 15-cm and 30-cm soil depth estimated smoldering probabilities (b).

mixed results. Although a minimum KBDI value of 600 on the Pocosin Lakes site was consistent with the high estimated smoldering potentials of root-mat soils, it was not consistent with minimum moisture contents greater than 300% and the corresponding low smoldering potentials of both soil depths (Fig. 11). On the Lake Worth Road site, a maximum KBDI value of 581 was consistent with smoldering potential of 15-cm soil depth and moistures of less than 250% but not with the low smoldering potentials of soils with moisture content exceeding 300% in the 30-cm-depth soils at the Lake Worth Road site and both soil depths on the Long Curve Road site in August and early September.

Precipitation in 2006 was slightly lower than the long-term cumulative monthly averages throughout most of the year, and the maximum estimated soil smoldering potentials were lower than in either 2005 or 2007. The smoldering potential was lowest on the Croatan NF and Pocosin Lakes sites during the summer months and was the result of soil moistures greater than 350%. A maximum KBDI value of 483 for the Croatan NF suggests the soils were at moisture contents that would support low levels of consumption but this value was not consistent with the high soil moistures on the site at that time. The KBDI values on the Pocosin Lakes site in late June were below 400 and were consistent with the low muck soil moistures, but that value did not reflect low root-mat moisture contents with an estimated smoldering potential range of 35 to 72% at that time.

The results of comparisons between estimated smoldering potentials and maximum KBDI values for DCBR sites were mixed. On these sites in 2006, the maximum KBDI value of 537

agreed with the smoldering potential of 37% and soil moisture of less than 225% for the 15-cm soil depth on the Lake Worth Road site. However, the maximum KBDI at that time did not agree with smoldering potentials below 10% and minimum moisture contents greater than 300% for the 30-cm soil depth or both soil depths on the Long Curve Road site.

The maximum KBDI value on the Hofmann Forest was 432 in early September of 2006, and it was consistent with low estimated smoldering potentials of the root mat and soil moistures and the lower estimated potentials on the Pocosin Road site at that time.

In 2007, precipitation was below the long-term cumulative monthly averages throughout the year and estimated smoldering potentials were higher than potentials in either 2005 or 2006. The results show that although soil moisture in 2007 decreased steadily throughout the first half of the year, it decreased at a faster rate from August through early November. By late July, the smoldering potential of root mat and muck soils on all sites was low but increasing. By late October, the smoldering potential of root mat and muck soils was high on all sites except the Croatan NF site. Although the watertable on the Croatan NF site decreased by 35 cm from August through November, the moisture content of both soil depths remained above 325%. A maximum KBDI value of 593 in October did not agree with the high soil moisture content on that site at that time.

In contrast with the low smoldering potential of the Croatan NF study site, the smoldering potential of the 30-cm-depth soil at the Wide Open Road site was above 60% whereas the smoldering potential of the Pocosin Road site was above 40%.

A maximum KKDI of 611 and low soil moistures on these sites suggest that the organic soils would support significant consumption. At that time, higher maximum KBDI values of 662 and 632 were reported for the Pocosin Lakes site and DCBR sites but higher soil moistures on these sites suggest lower risk at that time.

Discussion

The results show that the KBDI is not a reliable predictor of ground fire potential. The index frequently overestimated smoldering potential in root mat and muck soil but did not underestimate smoldering potential during the present study. Because the index is a function of meteorological inputs, the sensitivity of the KBDI to local soil, plant community and hydrologic influences is limited.

In addition to drought indices such as the KBDI, soil moisture and the depth of the watertable are common but inconsistent measures of ground fire potential. Our investigation shows no clear relationship between minimum root-mat moisture and maximum watertable depth. The minimum root-mat moisture contents on the Pocosin Lakes site in 2005 and 2006 were lower than the minimum moistures on the Hofmann Forest sites even though the watertable was closer to the surface on that site. Similar results were found on the DCBR sites in 2007 where root-mat moistures on the Lake Worth site were lower than the moisture contents of the Long Curve site even though the watertable was closer to the surface on that site at that time. Gilliam and Skaggs (1981) reported watertable levels on similar undeveloped pocosin study sites usually did not become high enough to affect the root-mat moisture.

Root-mat moisture sampling was limited but the results suggest that root-mat moisture content was not influenced by watertable depths during the summer months. Because root-mat moistures were collected at 2-week intervals, understanding of the interrelationships of precipitation, root-mat moisture, watertable dynamics and smoldering potential is incomplete. Additional study of the continuous responses of root-mat moistures and watertable dynamics may improve the predictability of smoldering potential in this upper soil horizon.

Watertable depths responded to yearly precipitation differences and our results were similar to the ranges reported in studies of similar sites (Daniel 1981; Skaggs *et al.* 1991; Gregory and Webster 2005). Studies of pocosin hydrology suggest several explanations for the differences in watertable dynamics, including evapotranspiration demand, soil properties, tidal influences and artificial drainage (Boelter and Verry 1977; Daniel 1981; Skaggs *et al.* 1991).

Boelter and Verry (1977) reported higher evapotranspiration in shrub-dominated communities when compared with forested communities of northern peatlands. Our measurements show maximum watertable depths were lower on the shrub-dominated Wide Open Road and Lake Worth Road sites than watertable depths on the overstorey canopy-dominated Pocosin Road and Long Curve Road sites. However, the watertable and soil moistures were consistently higher on the Croatan NF site, which is also dominated by shrubs.

Watertable response to precipitation under shallow watertable conditions, which is characteristic of pocosin wetlands, is a function of available water storage capacity and soil drainable

porosity (Skaggs *et al.* 1991). Surface flow and runoff losses are higher when the watertables are closer to the surface and available water storage capacity is low. An important component of soil water storage in wetlands is drainable porosity, which reflects watertable change and the volume of water drained from the saturated soil by gravity (Skaggs *et al.* 1991). Because soil drainable porosity increases with depth, soil moisture response to precipitation and evapotranspiration are expected to be similar on sites with similar watertable depths.

Although the general patterns of watertable depth and soil moisture response to yearly and seasonal precipitation differences were similar, the relationship between maximum watertable depths and minimum soil moisture was not consistent. In 2007, the maximum watertable depths on the Croatan NF site and Long Curve Road site were 74 and 70 cm below the ground surface, respectively. Soil moistures of the 15-cm depths decreased on the Croatan NF site from near-saturation levels in January to 330% in October with low smoldering potential at that time. The soil moistures on the Long Curve site decreased to 164% from near-saturation in January to a greater than 50% potential of sustained smoldering. A similar response was present in comparison of the 2005 Lake Worth and Pocosin Lakes sites, where the watertable of the Pocosin Lakes site was 30 cm deeper than the Lake Worth site but 15-cm soil moisture contents on the latter site were 32% higher.

Factors other than soil properties may constrain soil moisture changes on these sites. Tidal influences on watertable levels on similar sites were reported by Daniel (1981) and may be an important factor on the DCBR sites because of their low elevation and close proximity to the Pamlico Sound. Artificial drainage networks also impact the hydrologic inputs and outputs to many pocosin wetlands (Richardson 1983). Gregory and Webster (2005) reported that changes in water flow patterns on the Dare County peninsula resulted from drainage networks developed for timber and resource management. The preliminary results of the present study show it is unlikely that a single factor is sufficient to explain site differences in soil moisture and watertable dynamics across all sites.

Soil water storage is an important factor in the evaluation of fire danger in Pocosin communities. It influences organic soil smoldering potential and live fuel moisture content of the associated plant species. Pocosin water storage is highly seasonal and it is dominated by the balance between water inflows of precipitation and outflows by evapotranspiration, surface flow and groundwater flow (Mitsch and Gosselink 1993). High levels of water storage are common in the winter and early spring when precipitation exceeds evapotranspiration, and lower levels of water storage are common in the late spring and summer when evapotranspiration is high and rainfall is less consistent (Daniel 1981; Skaggs *et al.* 1991). Our results show that during the period of highest fire frequency in March and April, the watertable levels were closest to the surface and soil moistures during that time were at levels with low estimated probabilities of sustained smoldering.

Daniel (1981) reported that differences in water-budget components below the regional scale were primarily controlled by differences in soil types, plant cover and wetland development.

During the present study, the maximum watertable depths from May through September were generally deepest on the

Hofmann Forest and Pocosin Lakes sites and closest to the soil surface on the DCBR and Croatan NF. Differences in watertable and soil moisture responses suggest the influences of seasonal and yearly differences in precipitation, site hydrologic factors and soil properties.

The results of the present study show that the KBDI index is not sensitive to site or root-mat and muck soil property differences and suggest that improvements in the ability to evaluate fire danger in pocosin or other wetland communities may result from the integration of meteorologically driven drought indices, such as the KBDI, with hydrologic factors that reflect water storage and movement.

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